A CHAT ABOUT TRANSVERSE *e-p* INSTABILITY

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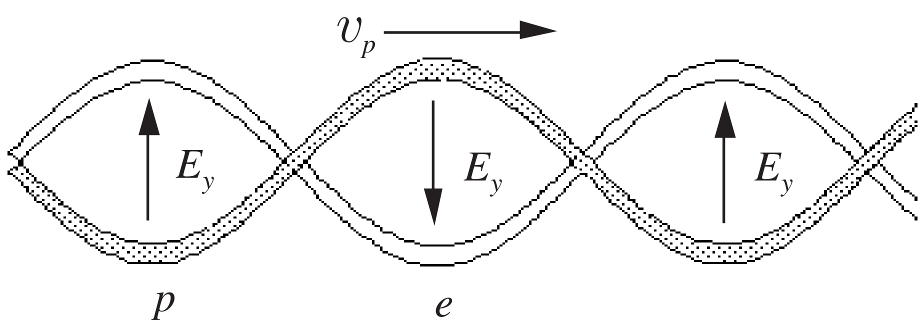
Snowmass 2001
July 2-20, 2001

1. A Sketch of *e-p* Instability

Basic Mechanism - Two Stream Instability

1.1 Physical Mechanism - A Simple Picture

(1) The instability is caused by the resonant transverse motion between the electrons and the proton beam.



Protons oscillate in betatron frequency ω_β.

The electron bounce frequency inside the proton beam is

$$\omega_e \approx (c/a)\sqrt{2r_e\lambda_p} \ ,$$

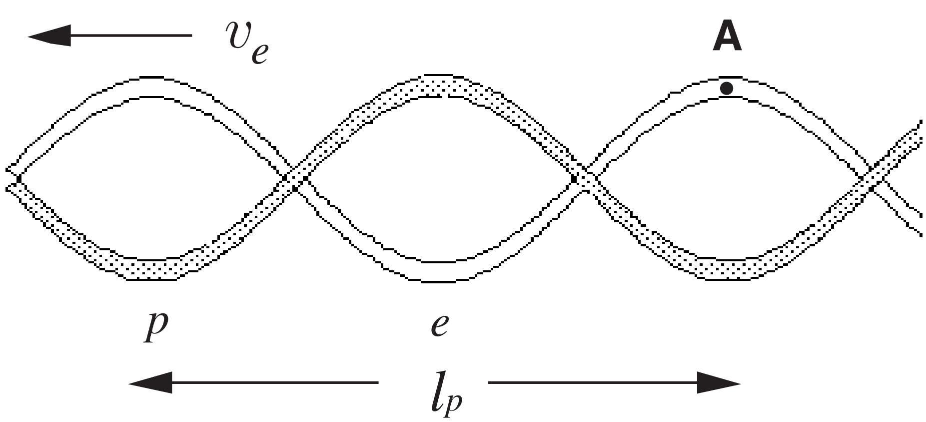
c = speed of light, a = proton beam radius,
r_e= classical electron radius, λ_p= proton line density.

Stable for $v_p = v_e$ and zero external force.

(2) When $v_p \neq v_e$, instability may occur.

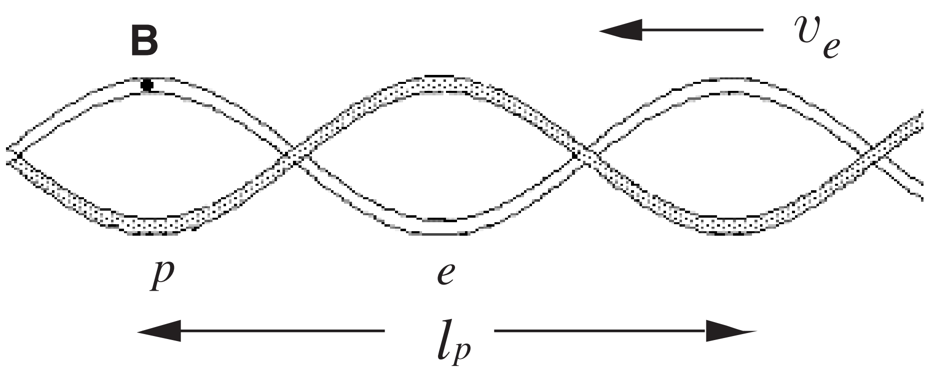
Resonance condition: $2\pi/l_p \approx \omega_e \big/ \left| v_e - v_p \right| \propto \sqrt{\lambda_p}$.

When $v_e = 0$ and $v_p \neq 0$, $2\pi/l_p \approx \omega_e/v_p \propto \sqrt{\lambda_p}$ for instability. In the beam frame $v_e = -v_p$,



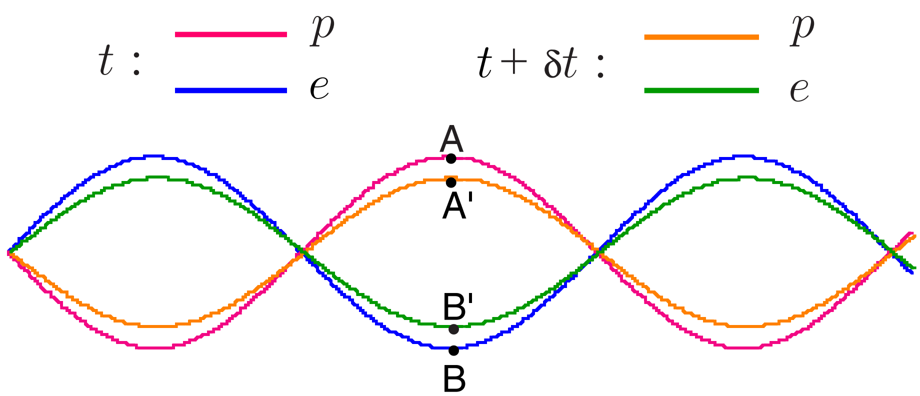
$\omega_\beta << \omega_e$ for intense beams, protons move only a fraction of their oscillation in one electron bounce.

After one electron bounce:



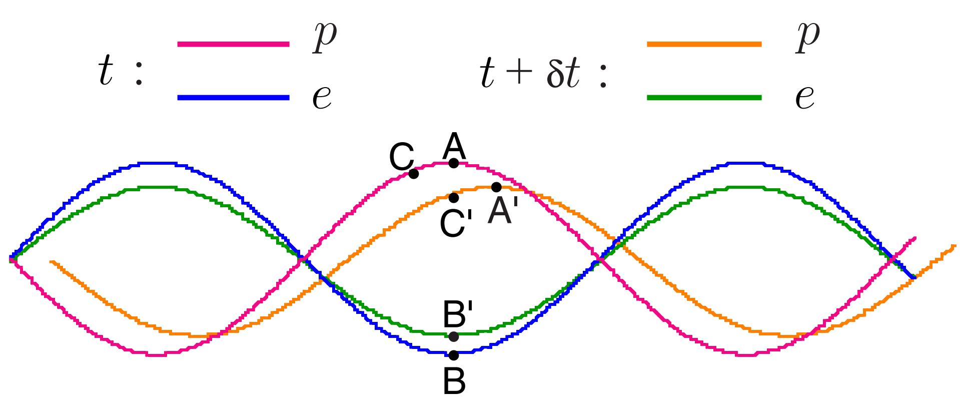
(3) Why need $v_p \neq v_e$ for instability?

$v_p = v_e$



$$\frac{d^2 Y_e}{dt^2} = -\omega_e^2 D(A', B') \ ,$$

$v_p \neq v_e$



$$\frac{d^2 Y_e}{dt^2} = -\omega_e^2 D(C', B') = -\omega_e^2 D(A', B') + \delta F \ ,$$

δF is sinusoidal - can drive electrons into resonance.

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(4) Has many experimental observations.

Has good linear analytical theory for continuous beams and very simple analytical theory for bunched beams.

1.2 Electron Sources

Background gas scattering

H^- Injection and beam-foil scattering (localized)

Secondary emission from lost protons

Electron multipactoring

Almost no analytical theory for combined electron generation and beam dynamics.

1.3 Possible Candidates

ISR, BEVATRON, PSR, AGS, AGS Booster, ISIS, KEK-PS Booster

SNS Ring, JHF Booster, ESS Ring, Proton Driver

Not seen in AGS and ISIS.

Not certain in KEK-PS Booster. (per I. Yamane in [2])

2. **Experimental Observations** [1-3, 9, 15, 19, 26, 28-30, 32-37, 40, 41, 46]

Fast growing transverse oscillations of proton beam (accompanied by fast beam loss in PSR and AGS Booster)

In bunched beams, see broad oscillation frequency spectra with central frequencies $\propto \sqrt{\lambda_p}$.

Threshold and growth rate sensitive to vacuum (not in PSR)

Threshold and growth rate depend on clearing electrode voltage

Threshold depends on bunching rf voltage

Electron detectors or electrodes collect large amount of electrons when beam becomes unstable

<u>Examples of Observations at PSR</u>

Bunch beam instability signals

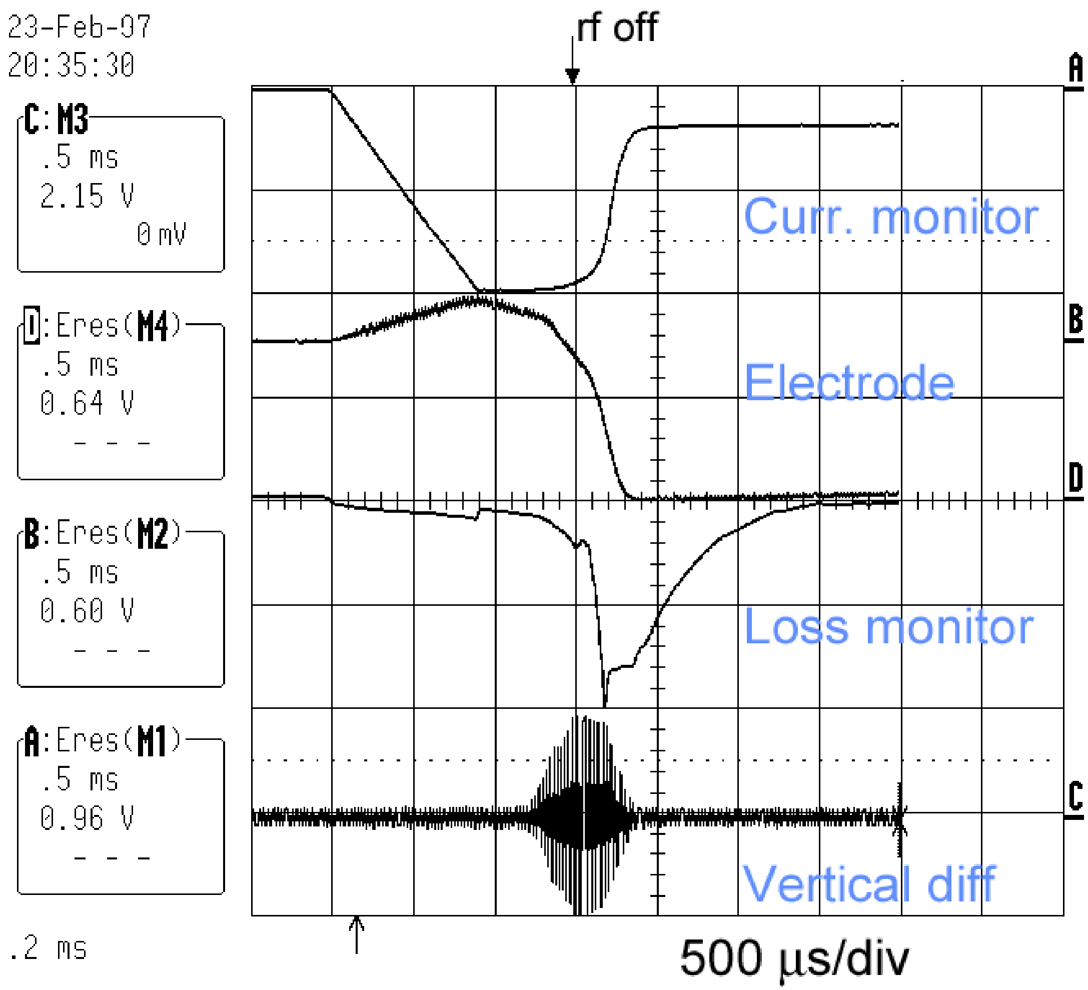
Vertical oscillations compared with beam density

Peak frequency vs. intensity

Electron signals

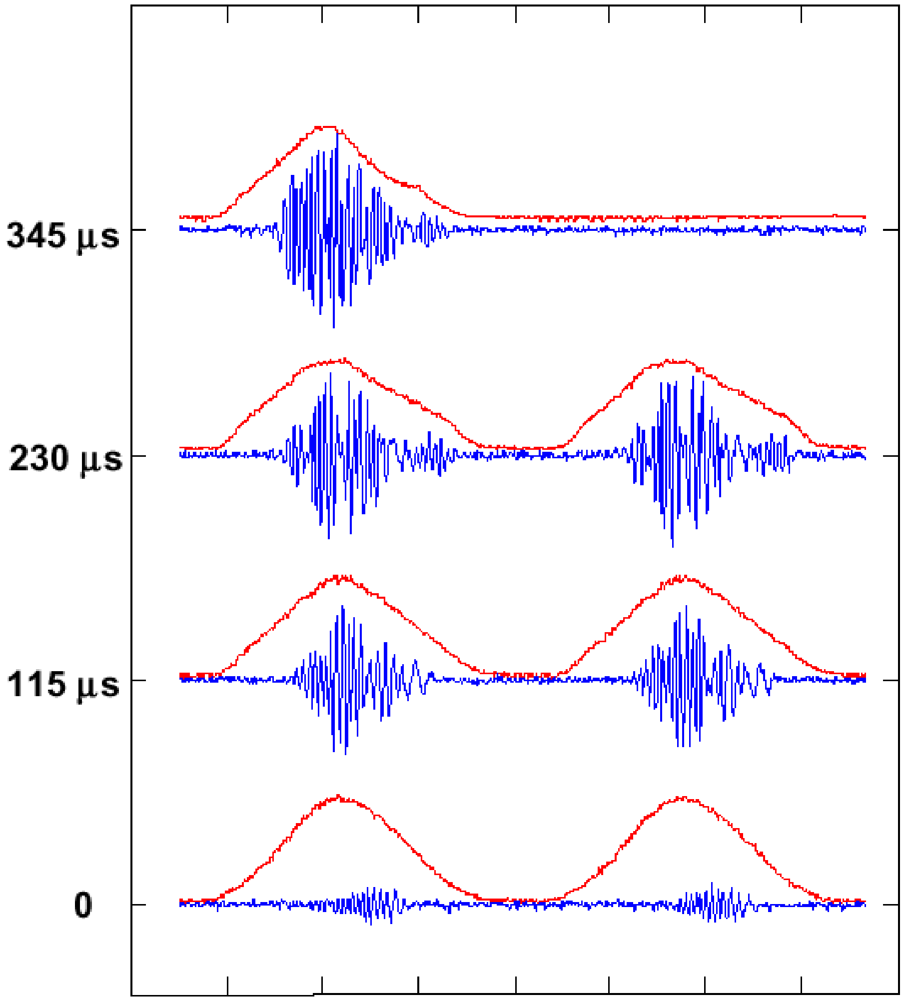
Figures from R. Macek and M. Plum

Bunched beam instability signals



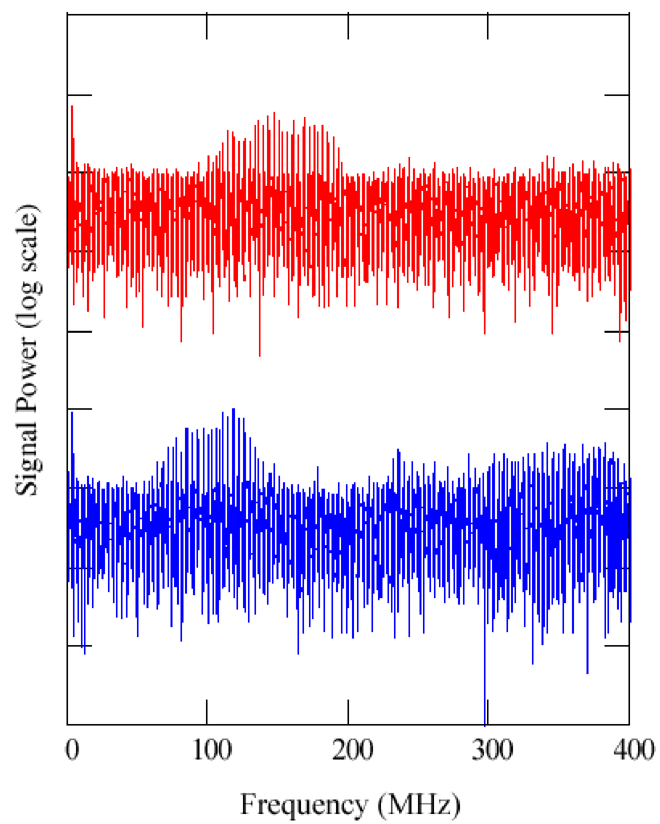
3.0 μC
925 μs injection
250 ns PW
6 kV rf
-1900 V opp. elec.

Vertical oscillations compared with beam density



- Vertical difference signals (blue) from a short stripline BPM and beam pulses from a wall current monitor (red).
  - WM41VD.4B
  - WC41.4B
  - Data taken Apr. 14, 1997
  - Data at t, t+115 μs, t+230 μs, t+345 μs

Peak frequency vs. intensity



- The peak in the signal spectrum depends on the beam intensity.
- Top spectrum is twice the intensity of the bottom spectrum
- Beam conditions for the top and bottom spectra are the same except for the beam intensity and the buncher voltage.

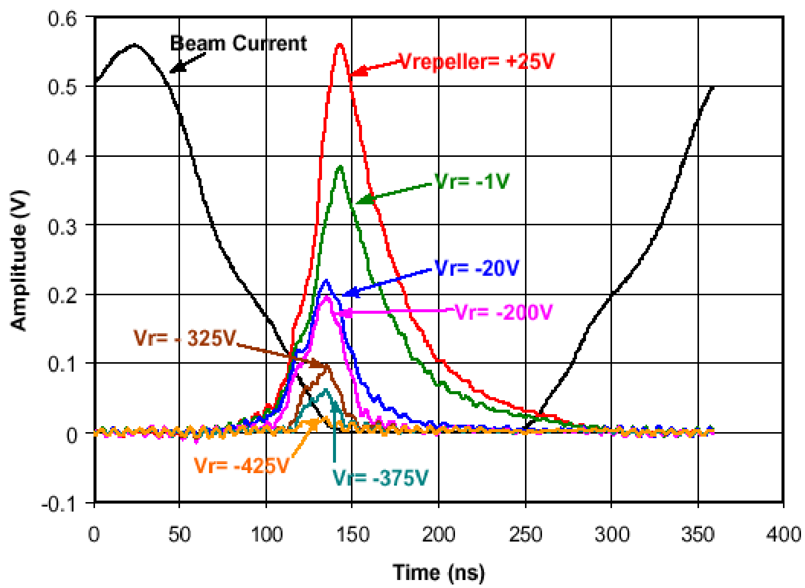
$$f = \frac{1}{2\pi}\sqrt{\frac{2Nr_e c^2(1-\eta_e)}{\pi b(a+b)R}}$$

SRWM41 ΔV from 13/Apr/97 data.
WM41VD.4C, SRWM41VD.4F

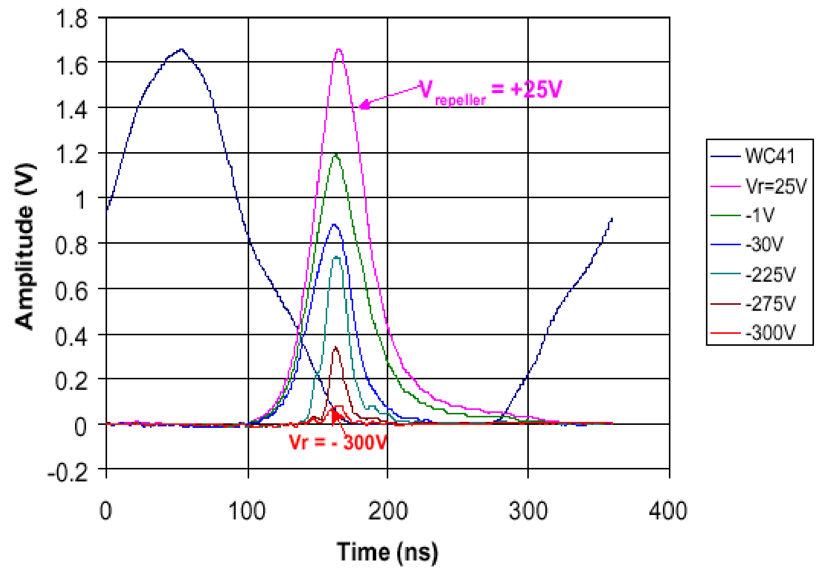
Electron signals

- **ED02X located just after stripping foil in section 0, ED42Y in straight portion of section 4**

ED02X for several repeller voltages
(8 μC/pulse beam)



ED42Y Signals for various repeller voltages
8 μC/pulse beam



3. **Theoretical Developments** [1, 2, 4-8, 10-14, 16-25, 27, 31, 32, 36, 38-45]

3.1 Analytical Studies

"Classical" Continuous Beam Analysis [7, 11, 12, 14, 21, 23, 27, 36, 38, 42-46]

Based on the dispersion relation derived from kinetic theory or centroid model of uniform line densities (frequency domain analysis):

$$(\omega_e^2 - \omega^2)\left[\omega_\beta^2 + \omega_p^2 - (n\Omega - \omega)^2\right] = \omega_e^2 \omega_p^2 f_e g_p \ ,$$

and its variations, where

ω_p = proton bounce frequency due to electrons (when ω_β= 0),
ω = frequency of the *e*-*p* mode,
n = azimuthal harmonic of the *e*-*p* mode,
Ω = proton revolution frequency,
g_p= function of proton oscillation frequency spread,
= 1 at zero spread,
f_e= function of electron oscillation frequency spread,
= 1 at zero spread.

Growth rate is given by $\mathrm{Im}(\omega) > 0$, instability threshold is found by solving $\mathrm{Im}(\omega) = 0$.

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Analysis for Long Bunched Beam [4]

Based on centroid model with non-uniform line densities

Treats the problem as initial value problem (time domain solution)

The solution for the proton centroid $Y_p(z',t)$:

$$Y_p(z',t) \sim \left\{J(z')/[\omega_\beta(t-z'/v_p)]^3\right\}^{1/4}\xi(z')\Phi(z'/v_p)$$
$$\times \exp\{-i\omega_\beta(t-z'/v_p)-\Delta_p(t-z'/v_p)-\Delta_e(z'/v_p)$$
$$+\sqrt{2\omega_\beta J(z')(t-z'/v_p)}-iJ(z')/4\} \ ,$$

where

$$J(z') = i\int_0^{z'/v_p}\frac{\omega_e^2(x)\xi(v_p x)}{W(x)}\Phi(x)\Psi(x)dx \ ,$$

$t =$ time, $i=\sqrt{-1}$, $\xi(z') = 2r_p c^2\lambda_e(z')/(a^2\gamma\omega_\beta)$,
z'= axial coordinate in the beam frame (origin at bunch head),
r_p= classical proton radius, Δ_p, Δ_e= the oscillation frequency spreads among the protons and electrons, respectively,
$\gamma = (1-v/c)^{-1/2}$, $W(x)$ = Wronskian of Φ and Ψ;
Φ, Ψ= linear independent solutions of the equation

$$\frac{d^2Y}{dt^2}+\omega_e^2(t)Y = 0 \ .$$

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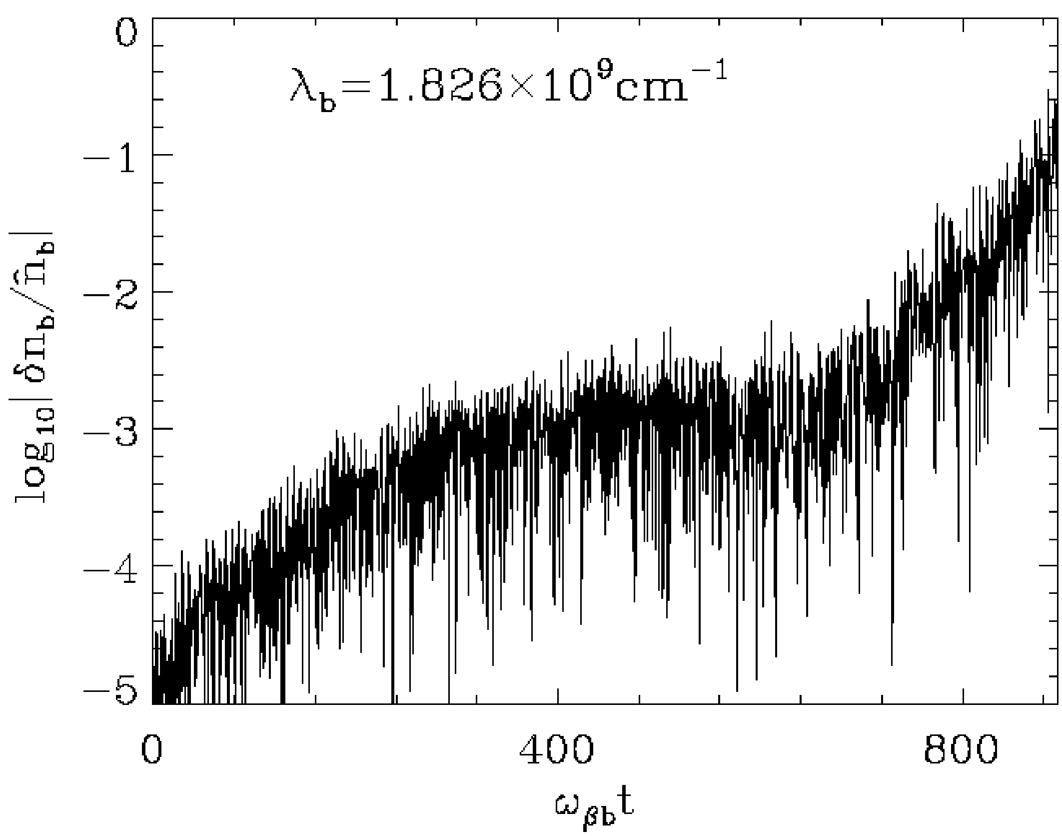
3.2 Computer Simulations

Continuous Beams [1, 5, 13, 16, 22]

Thorough 3d Δf simulations based on self-consistent equilibrium models compute mode configurations, instability thresholds and growth rates for both linear and nonlinear growth regimes.

Figure from H. Qin et al. [5]



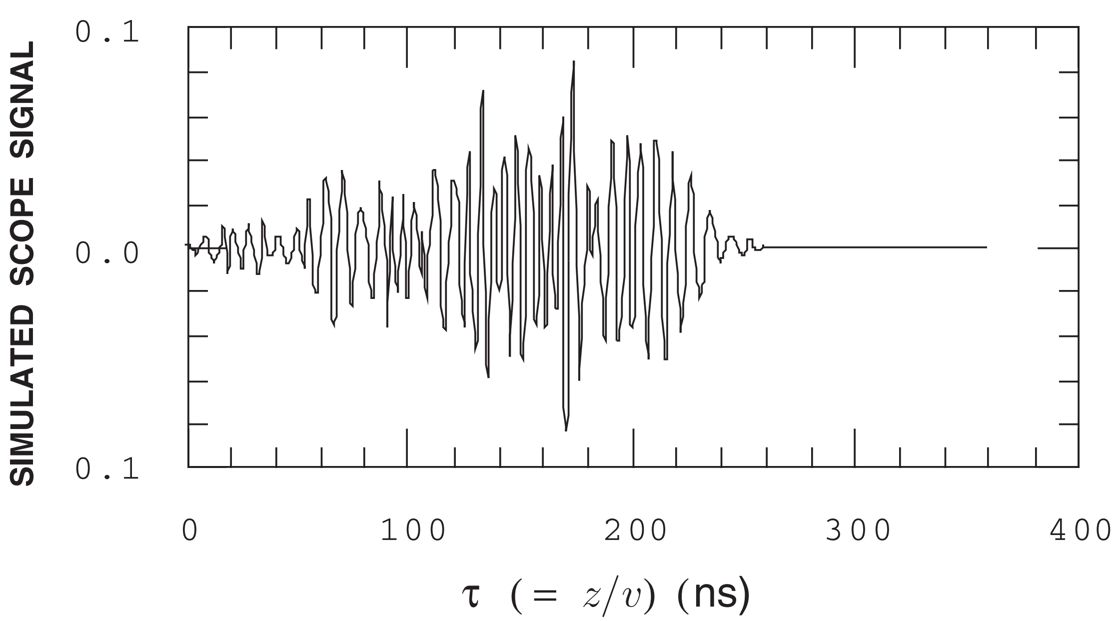
Single-Bunch Beam [1, 2, 17, 31]

1.5d simulations using centroid model and a simple electron SE model produce plausible simulated BMP signals. Main results:

e-p mode grows in both space and time. Frequency $\propto \sqrt{\lambda_p}$.

Proton beam carries the memory of oscillations. Resonant coherent electron motion develops in a few electron bounces. Multi-turn trapping of electrons is not a necessary condition for instability, but does lower the threshold.

Figure from T. Wang [31]



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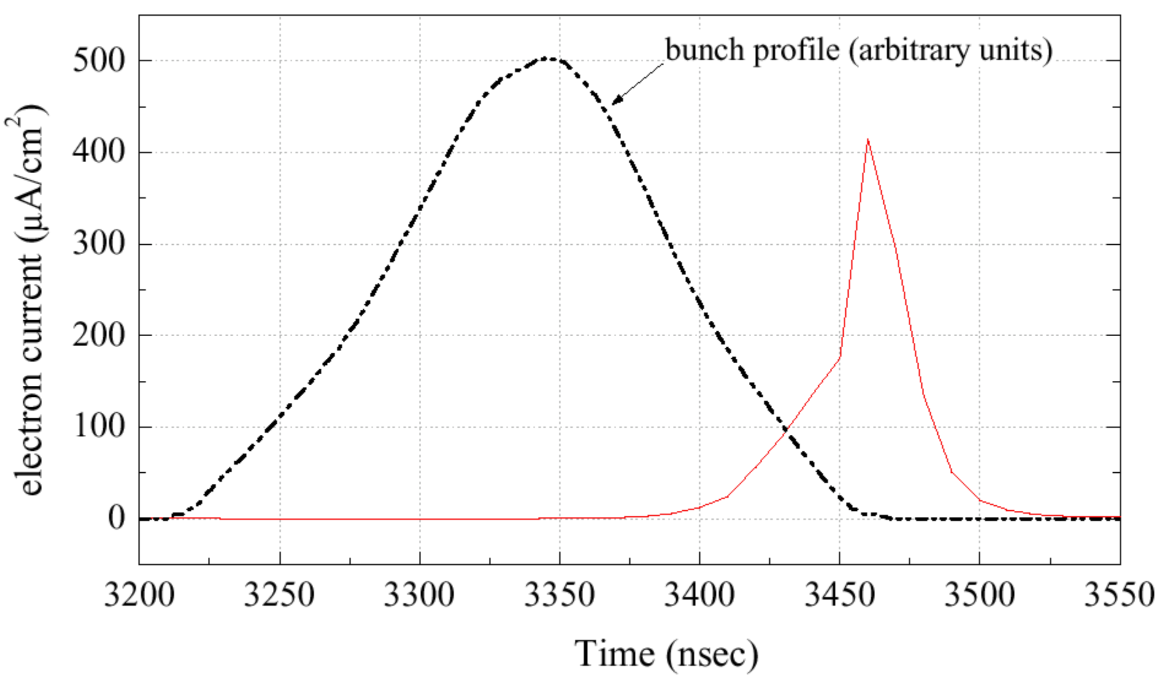
Electron Cloud Study [1, 6]

2d or 3d computations of electron dynamics using more detailed SE models for equilibrium proton beams. Produced electron detector signals and energy spectra similar to the observations in PSR.

Figure from M. Furman and M. Pivi [6]



4. Possible Preventions and Remedies

Good Vacuum	Has pronounced effect in ISR. Affects the beam stability in PSR little.
Landau Damping	Increase tune spread (more momentum spread or nonlinear lenses), or, couple x-y motion at the cost of emittance growth.
Clearing Electrodes	Effective in ISR.
Beam Shaking	Worked at ISR, but not for PSR. Causes emittance growth.
Active Damping	Partly worked in BEVATRON.
Solenoid	Demonstrated in KEK e^+-e^- collider for reducing trapped electrons.
TiN Coating	Decreases SEY. Seen at PSR as reduced number of electrons collected on the beam pipe.

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5. ISIS - PSR Puzzle

ISIS and PSR have some similarities. Still don't know why *e-p* instability not seen in ISIS for both bunched and unbunched beams at 10^{13} ppp.

Conjecture: the shielding due to the rf-cage (wires) may reduce trapped electrons (?)

Photo from I. Gardner

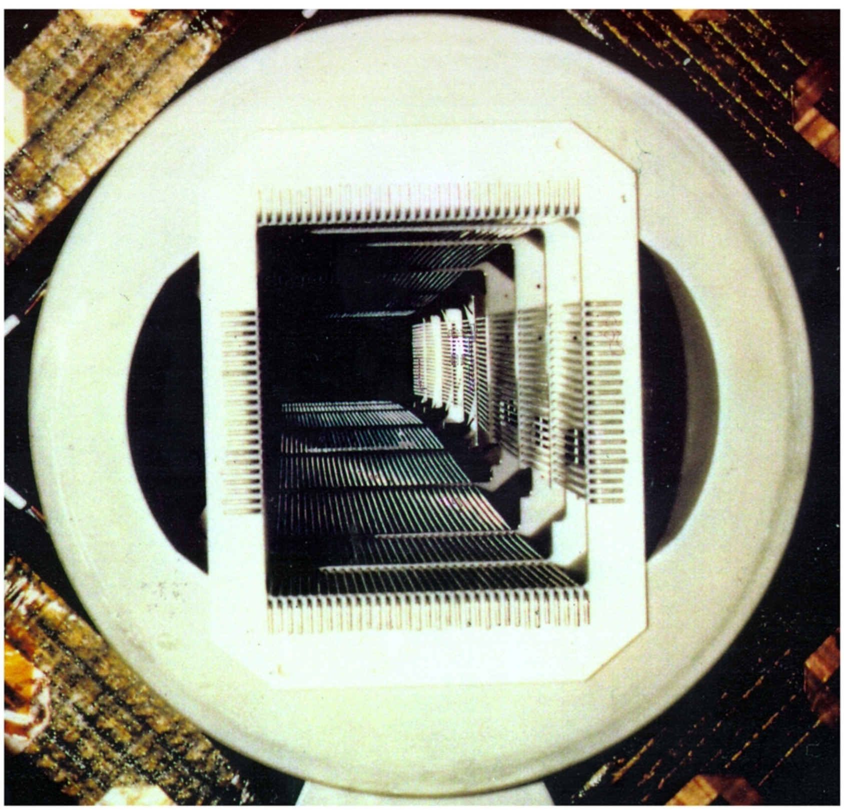
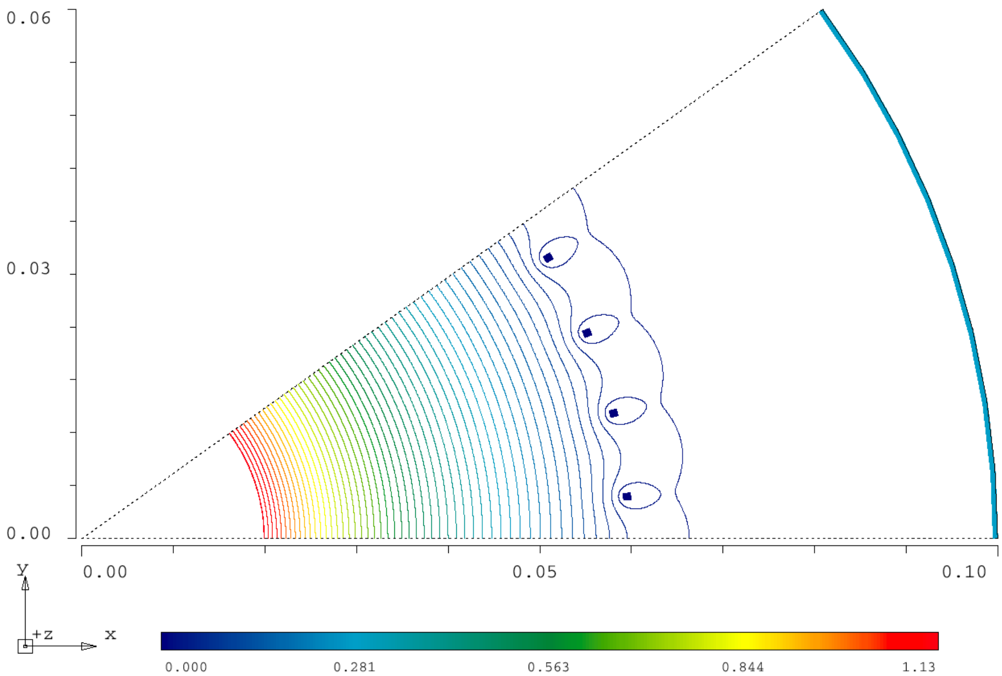


Figure from S. Kurennoy



6. References

The following is a list of publicly accessible papers directly related to the electron-proton (e-p) instability and the instability observed in the Proton Storage Ring at Los Alamos. Omitted from the roll are the individual internal reports like PSR Technical Notes as well as the technical notes from AT, MP and AOT Divisions of Los Alamos National Laboratory. The collection certainly is not inclusive, but it does contain the most of the important ones. Furthermore, this list is not intended to be a bibliography of the underlying physics and related methods of analyses. Thus, many papers in the areas of electron-positron instability, electron-beam and trapped-ion instability, and beam-plasma interaction, though discuss about the same type of physics and approaches of analysis with the e-p instability, are not included.

Proceedings:

1. Presentations at the ICFA 8th Beam Dynamics Mini-Workshop on Two-Stream Instabilities in Particle Accelerators and Storage Rings, Feb. 16 - 18, 2000, Santa Fe, New Mexico. In particular, Session I. Electron Cloud Effects and Two-Stream Instabilities at High Intensity, Medium Energy Proton Rings. Presentations can be accessed at the web site: http://www.aps.anl.gov/conferences/icfa/two-stream.html.

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